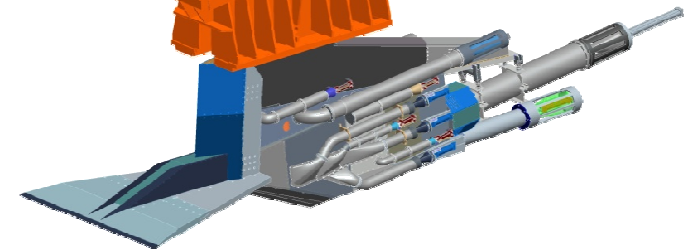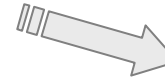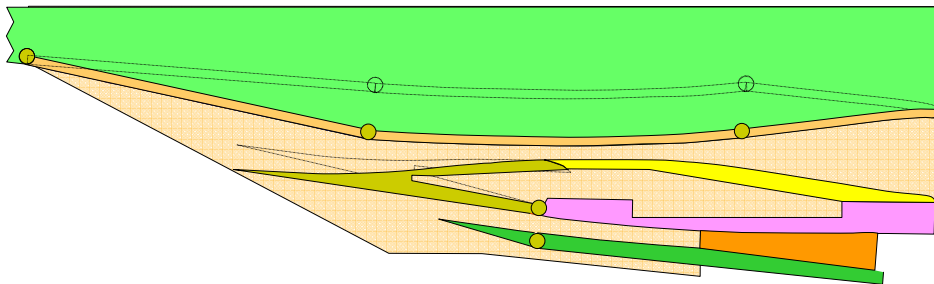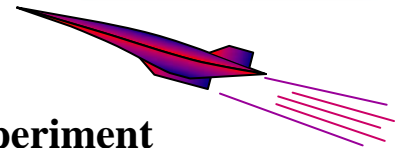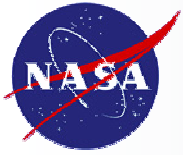# TBCC Inlet Experiments and Analysis

**(Initial Screening Results of a Small-Scale Inlet Mode Transition Experiment
and progress toward a Large-scale IMX testbed)**

October 31st 2007

Dave Saunders, John Slater, Vance Dippold & Jinho Lee
NASA Glenn Research Center
Cleveland, Ohio

Bobby Sanders & Lois Weir
TechLand Research, Inc.
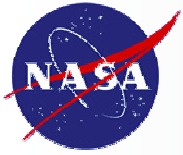North Olmsted, Ohio

Overview

Background, (definition, history & objectives)

TBCC Inlet Design, (dual flow path, constraints & CFD)

CFD Results, (validation, performance & test guidance)

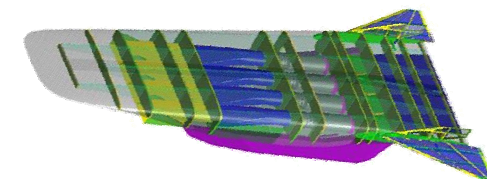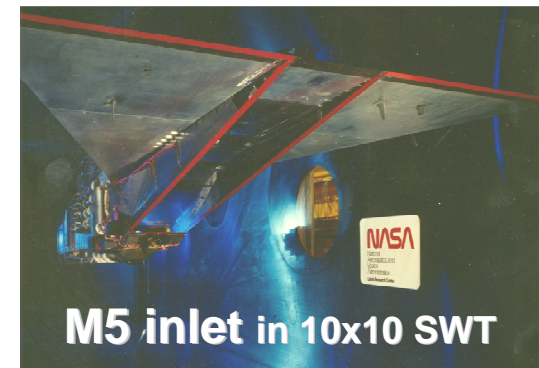1x1 SWT screening results (configurations, M4, & off-design)

Conclusions and 10x10 Large-scale tests

Background: (*TBCC=Turbine Based Combined Cycle*)

- Mode-transition: definitions (*IMX= **I**nlet **M**ode **X**,transition*)

- Previous/related programs:
    - M5, X43b
    - HiSTED, Robust Scramjet,
        RATTLRS, FALCON

- Over-under concept and TBCC

M5 inlet in 10x10 SWT

- Current effort: Two-pronged testing
    - (S) • IMX = small-scale
    - (L) • Large-scale Combined Cycle Engine (inlet/controls/engines)
        Collaborative effort with ATK/Boeing/Williams

- TBCC IMX Objectives

TBCC Inlet Research Objectives

- **L/s** • Research over/under split flow inlet for TBCC.
  - • Demonstrate mode transition at **S** small and **L** large-scales.
  - • Develop a integrated database of performance & operability.
    - **S** Low-speed inlet (sized for Mach 4 turbine engine).
    - **L** High-speed inlet (DMRJ for Mach 7 cruise)

- **L/s** • Validate CFD predictions for each inlet's design approach, and performance and operability prediction.

- **L** • Measure distortion characteristics throughout the mode transition Mach number range.

- **L** • Operability database for future mode transition controls research

- **L** • Testbed for integrated inlet/engine propulsion system tests

Inlet mode transition addressed by small & large-scale experiments

Inlet model requirements for CCET (Combined-Cycle Engine Testbed)

- Used 2D aerodynamic design and mechanical concept from small-scale IMX effort.
  - IMX, 'Inlet Mode Transition' is a small screening inlet model to qualitatively understand operability.
  - Key follow-on test is to get large scale data for quantifying performance, operability, controls development

- Forebody required roughly based on Mach 7 X43-b vision vehicles

- Facility selection: Turbine engine siziing requires large facility
  - GRC 10'x10' propulsion supersonic wind tunnel selected

- Remotely variable ramp and rotating HS&LS inlet cowls

- Over-travel LS cowl to allow M3 to M4 mode transitions

- Variable bleeds, bypasses to allow test flexibility and controls work

- Flow metering on both turbine flowpath **&** DMRSJ flowpaths

- Engines diameter of **~12"** chosen.
 - Mid-sized 12" engine being developed towards M4 in HiSTED, RATTLRS

12"

~36"

~30' long
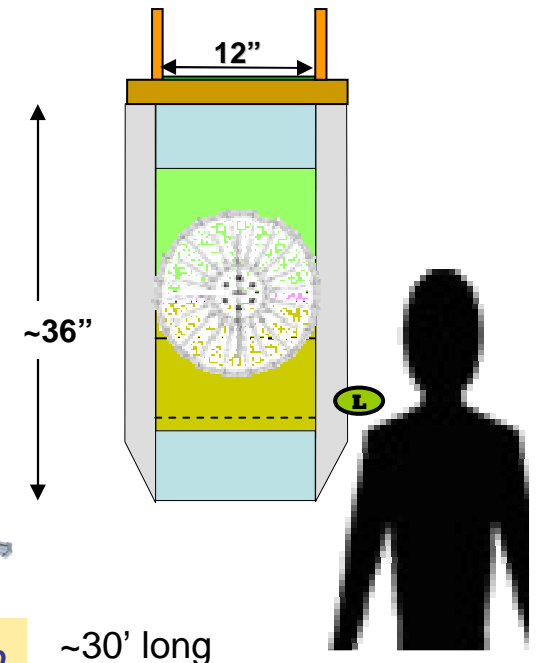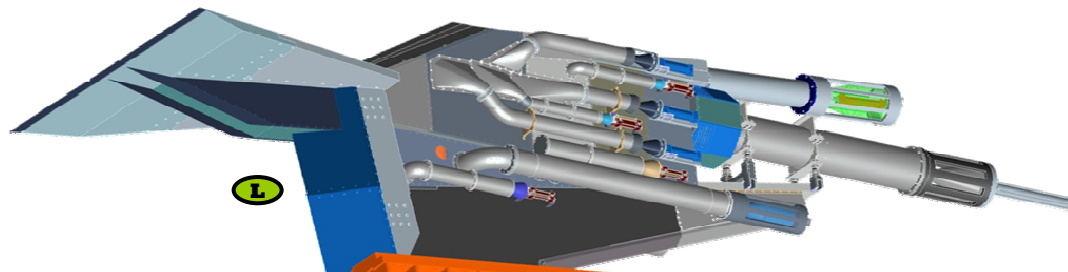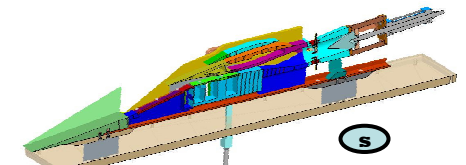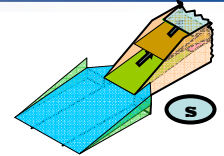
Inlet model provides 'strongback' for propulsion integration
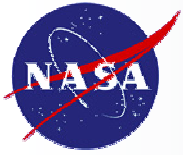
TBCC Inlet Design

- High-speed: (ref. Albertson/Emami/Trexler)

- Low-speed: supersonics / mixed comp. / bleed / visc.effect / YF-12 / XB-70 / SST>HSCT

- Integration: vehicle, turbofan, high-speed flowpath

- Mach 7 Hydrocarbon fueled Scramjet with Mach 4 transition from Turbine

- Historical recoveries / Flow splits / engine demand / mission

- Impact of CFD:
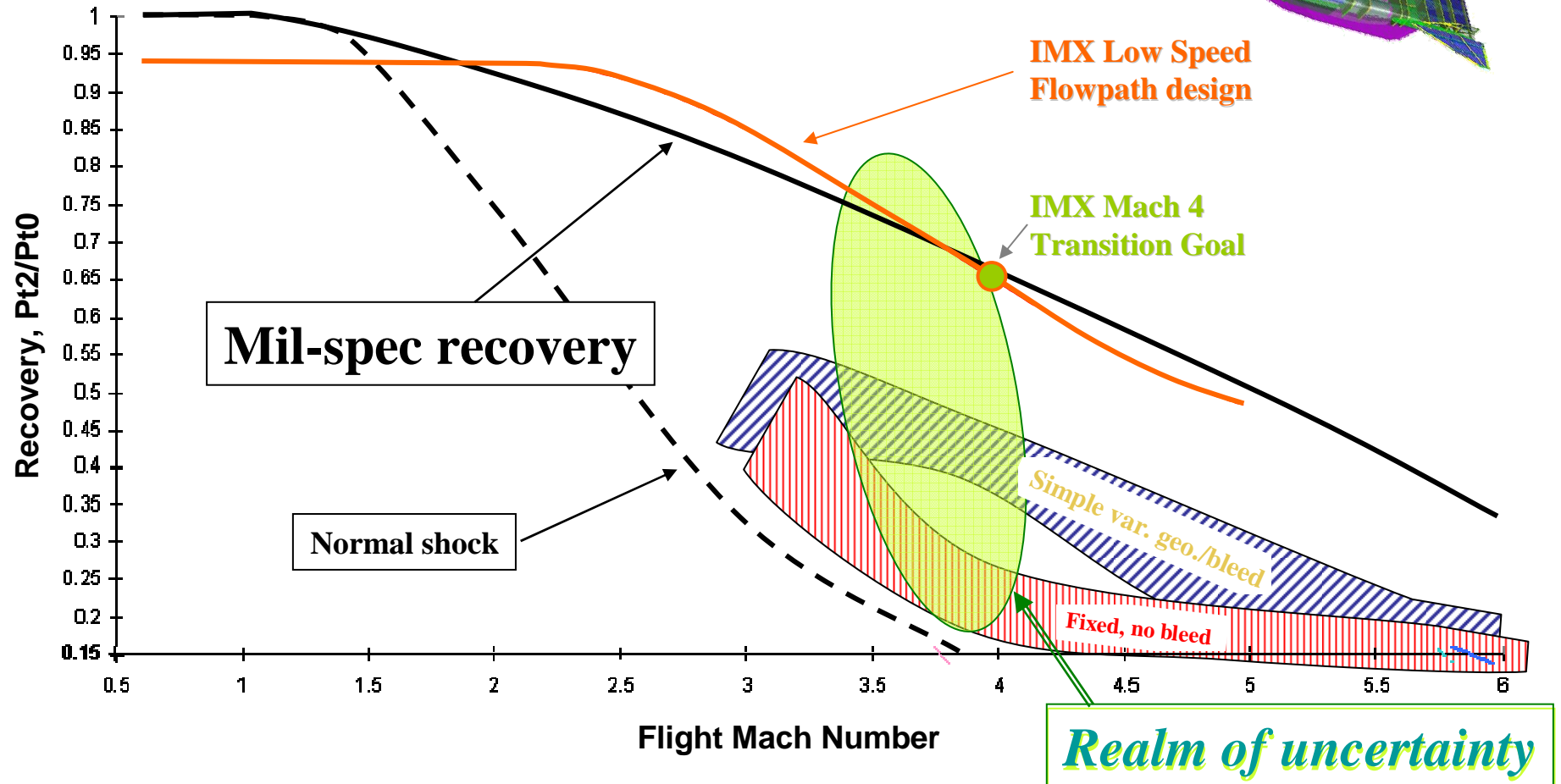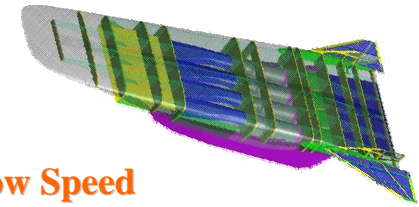   - Visualize, Instrument, Test plan,
    - Design, Controls
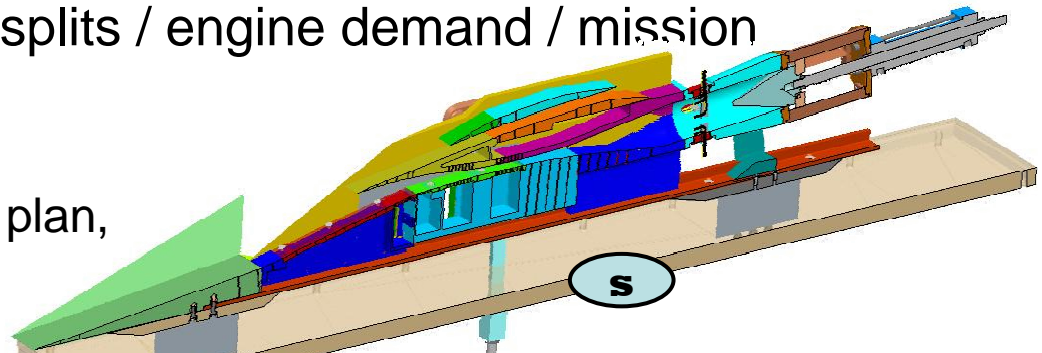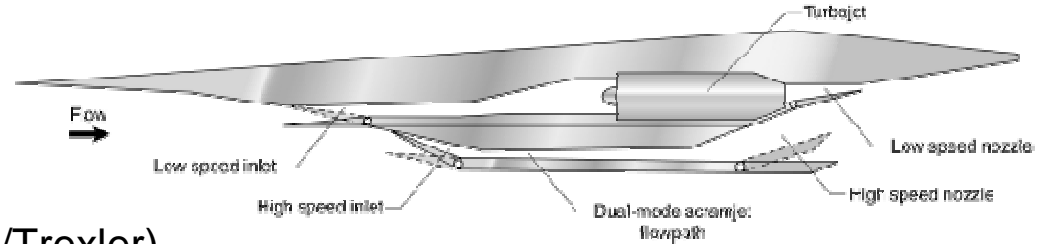
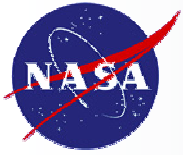*Inlet design driven by TBCC studies, CFD tools, and physical constraints*

Inlet Pressure Recoveries for TBCC, ?s

IMX Low Speed Flowpath design

IMX Mach 4 Transition Goal

Mil-spec recovery

Normal shock

Simple var. geo./bleed

Fixed, no bleed

Realm of uncertainty

Recovery, Pt2/Pt0

Flight Mach Number

Inlet performance can vary by 4x depending on inlet design

Mode transition sequences: *Mach 4 shock scenarios*

AOA = 4^0

Inlet Transition issues

Turbine spool down transient

LS external shock, Start-ability

Bleed modulation?

LS internal shock control

LS distortion

LS & HS Cowl position, Schedule or control

Buzz limits?

HS flame stability

HS normal shock, start-ability?

HS shock train management
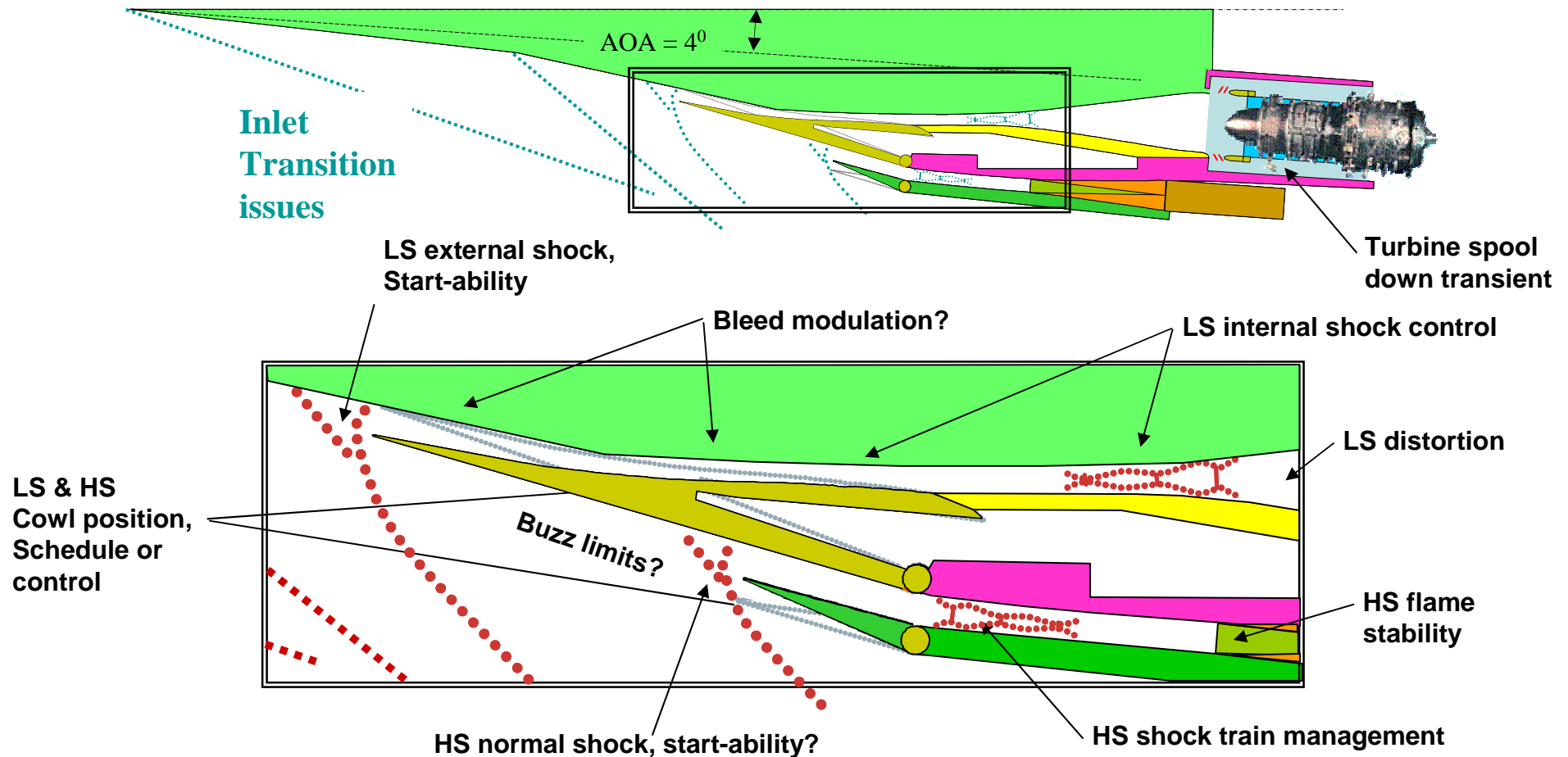
Mode transition design at Mach 4 has complex interations
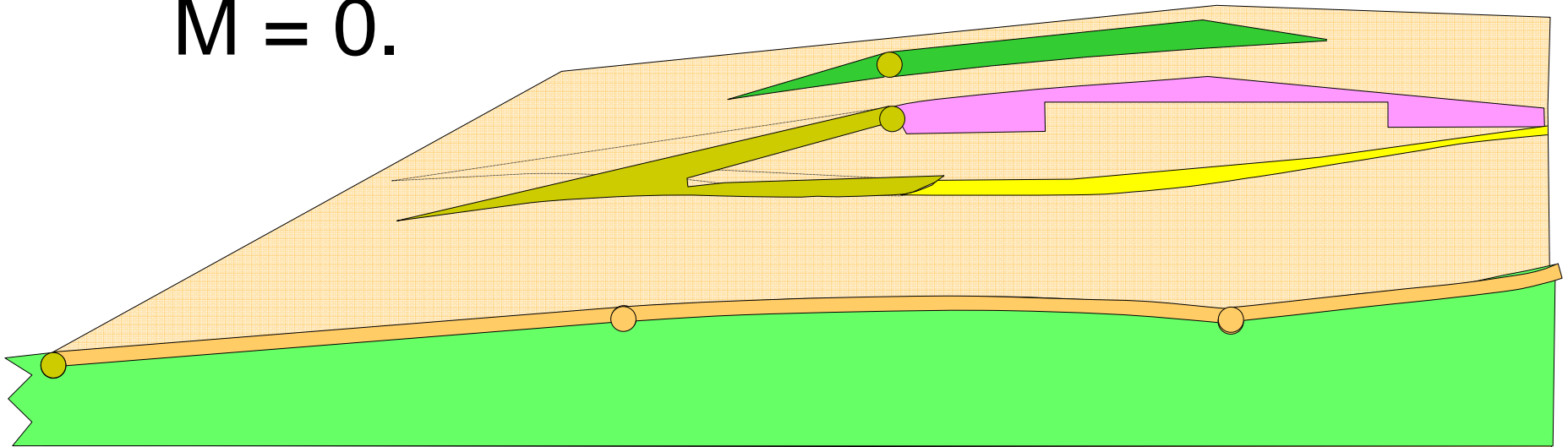
M = 0.

Mode transition sequences

Variable geometry ramp
inlet configurations.

Mach number / mode transition
with shocks

Mach 4

Mach 7

M = 2.

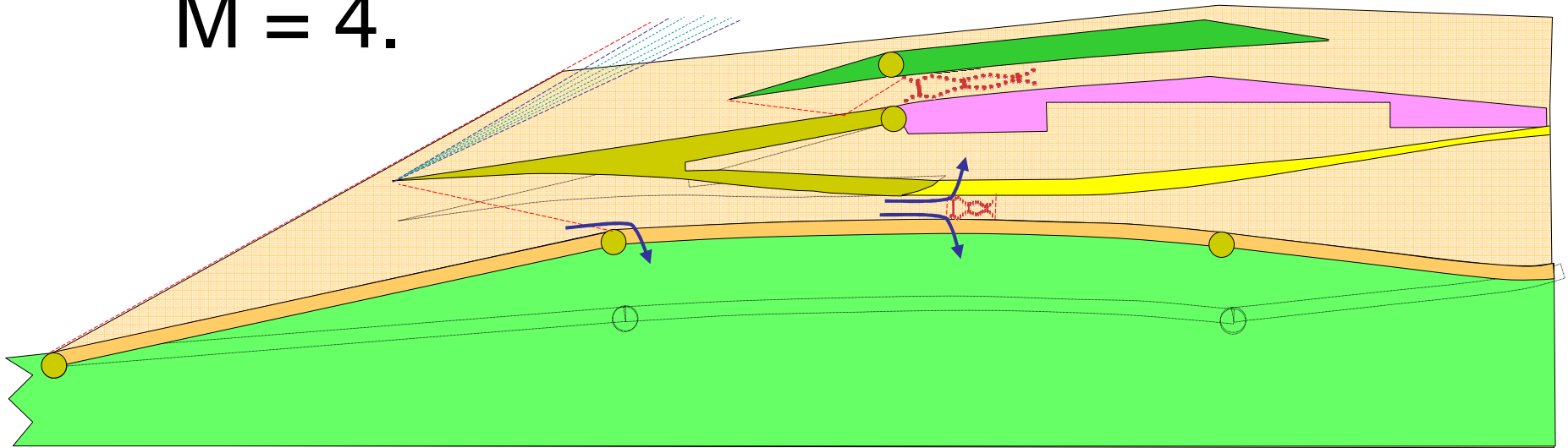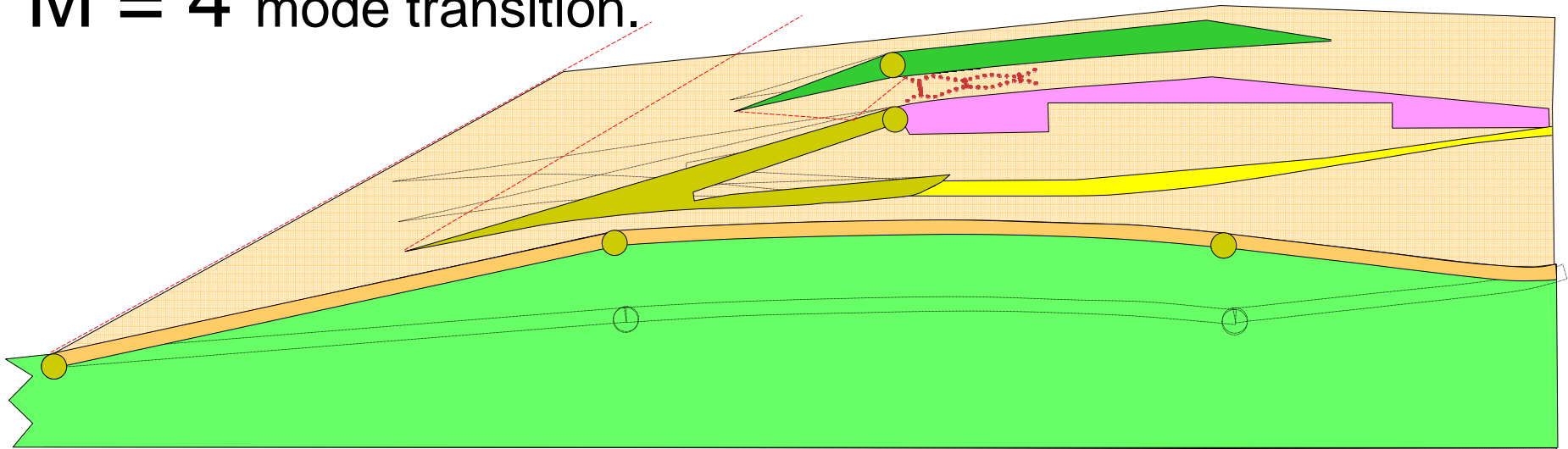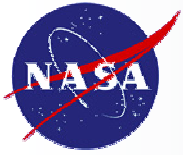Mode transition sequences

Variable geometry ramp
inlet configurations.

Mach number / mode transition
with shocks

Mach 4

Mach 7

M = 3.

Mode transition sequences

Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks

Mach 4

Mach 7

M = 4.
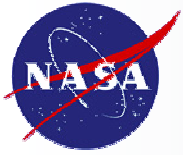

Mode transition sequences

Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks

Mach 4

Mach 7
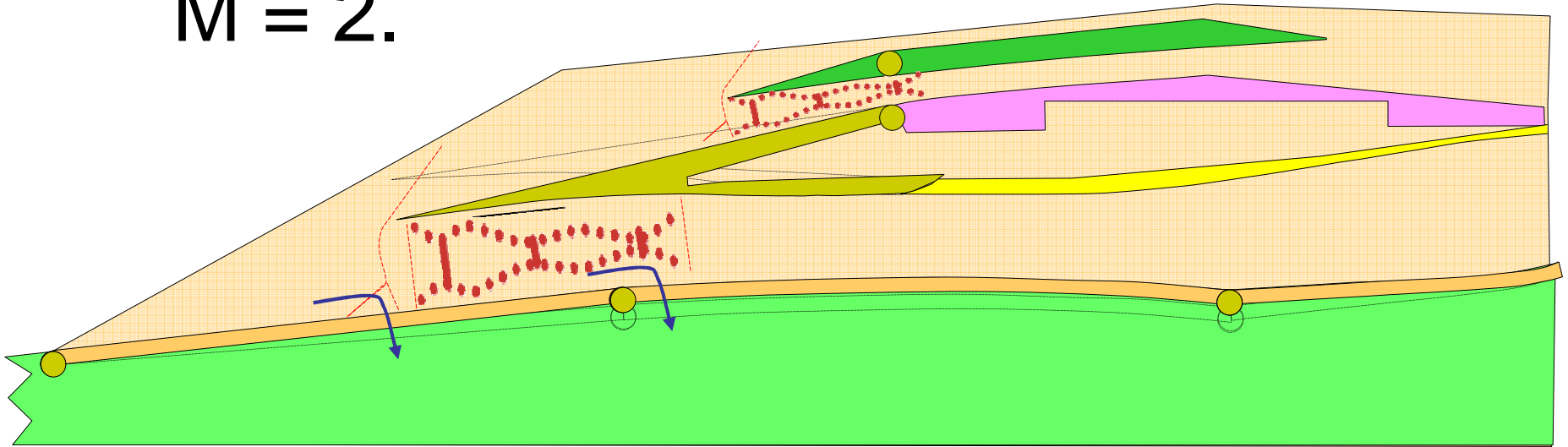
M = 4 mode transition.

Mode transition sequences

Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks

Mach 4

Mach 7

M = 4 low-speed closed.

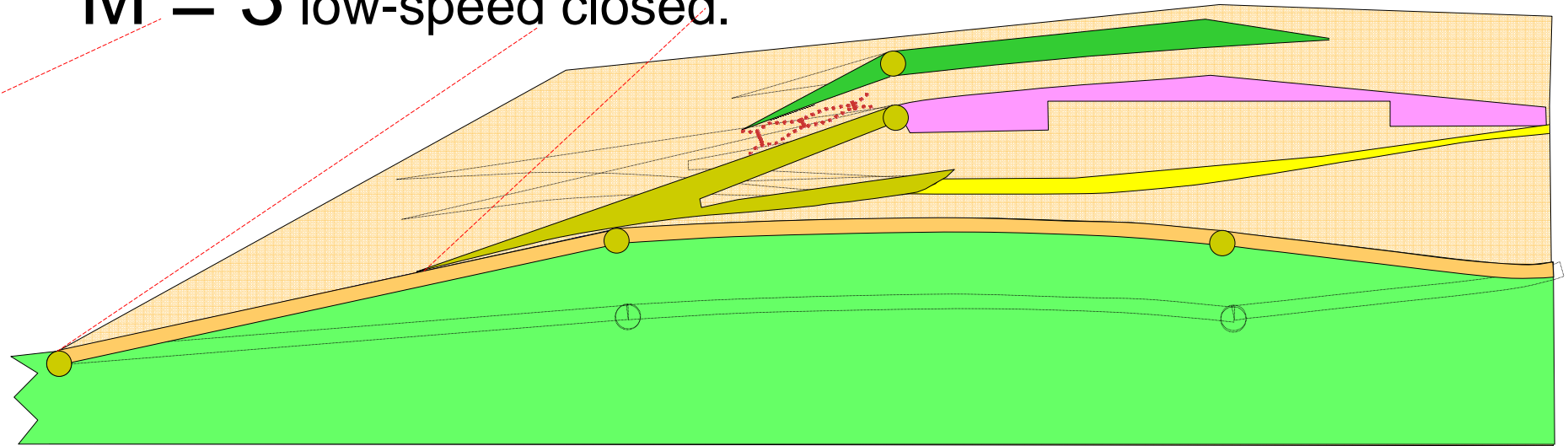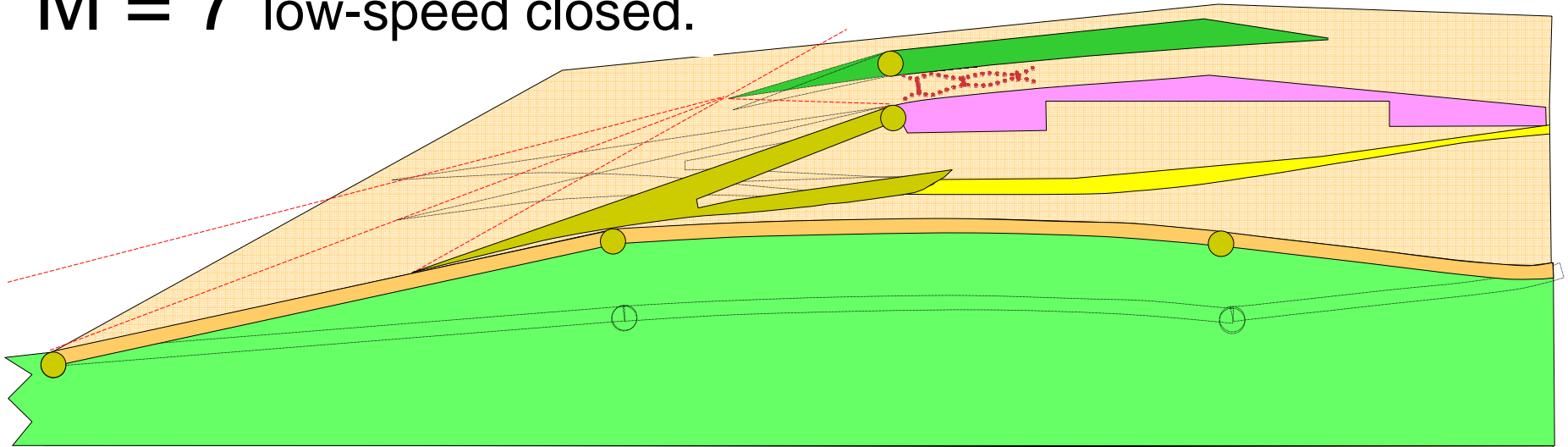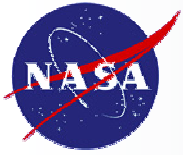Mode transition sequences

Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks

Mach 4

Mach 7
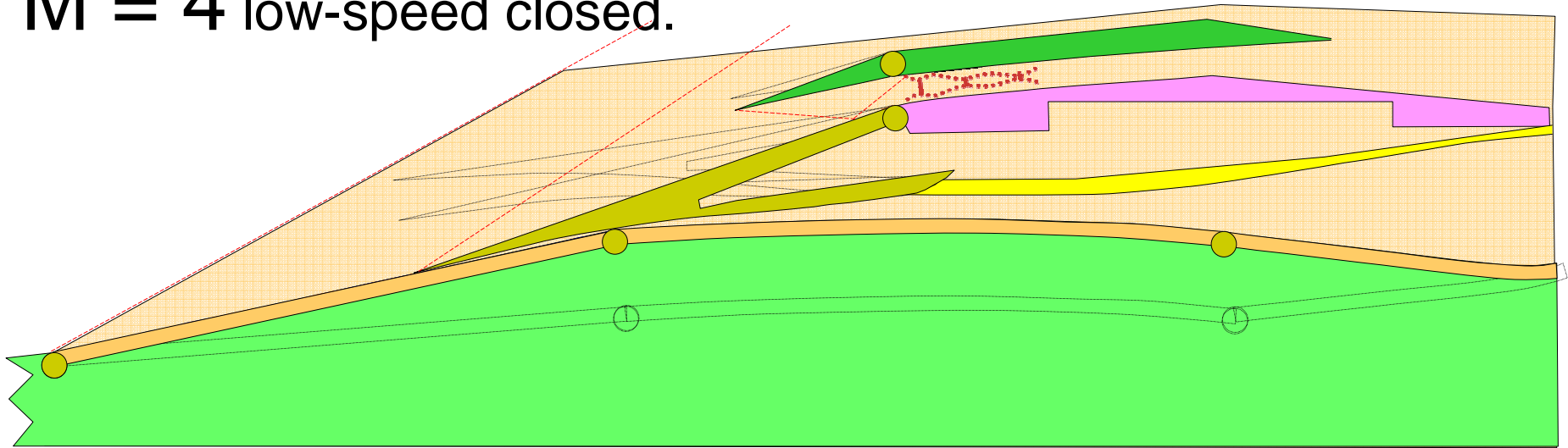
$M = 3$ low-speed closed.

Mode transition sequences

Variable geometry ramp
inlet configurations.

Mach number / mode transition
with shocks

Mach 4

Mach 7

M = 7 low-speed closed.

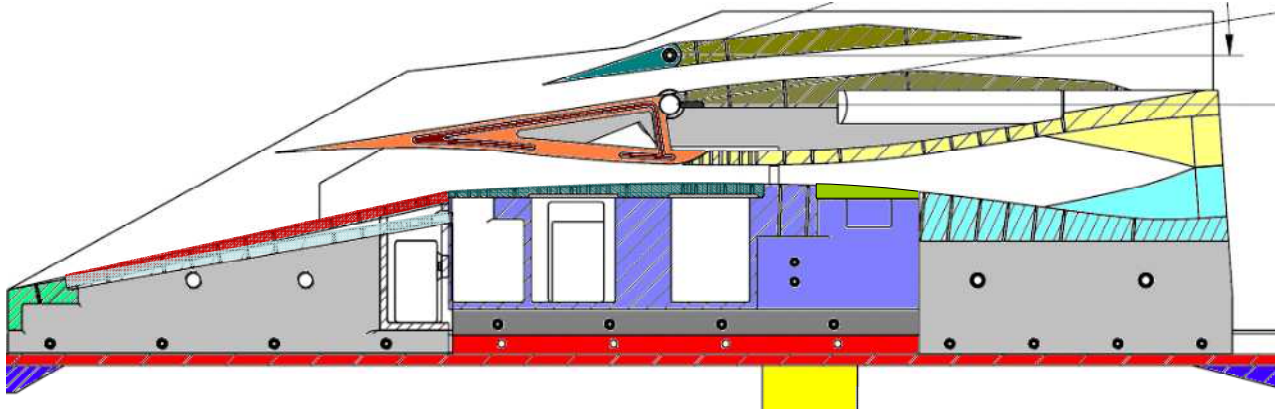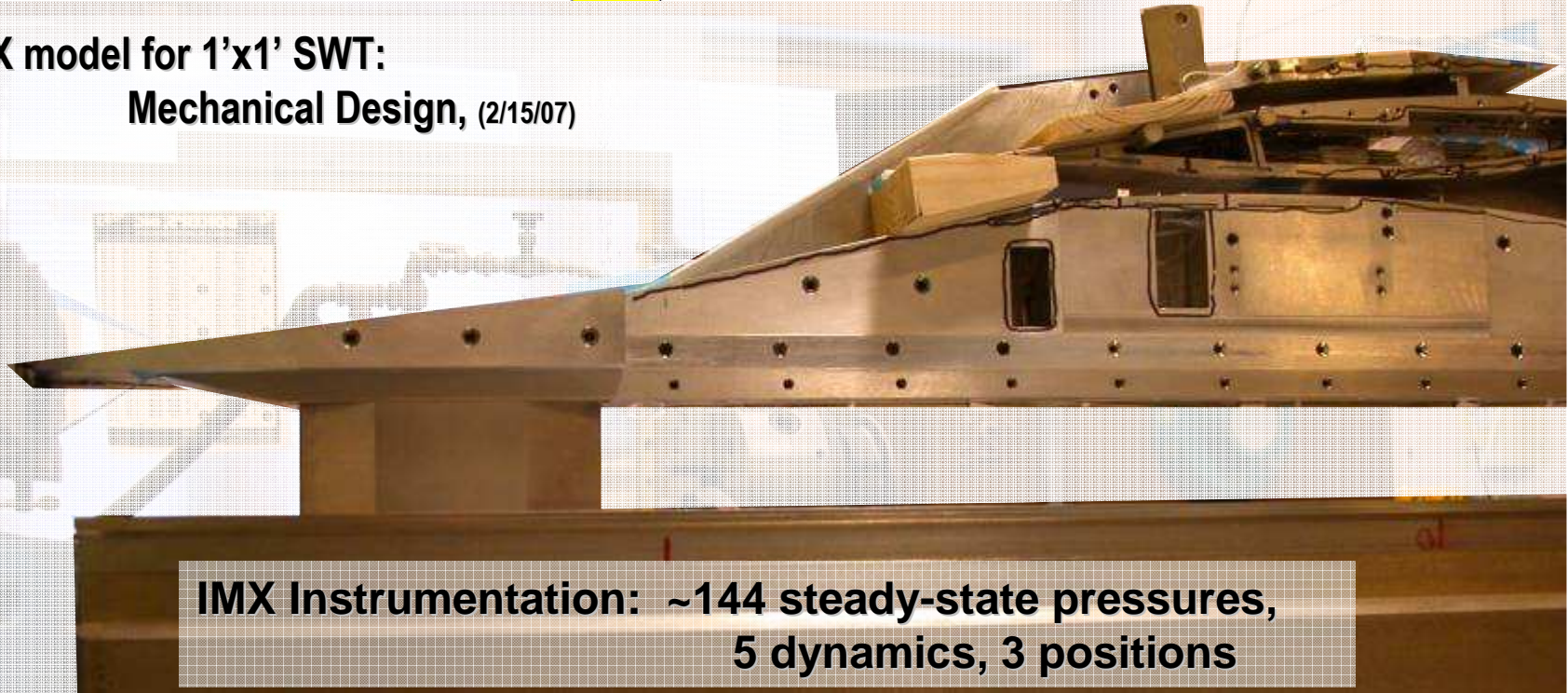Mode transition sequences

Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks

Mach 4

Mach 7

TBCC Inlet Experiments and Analysis

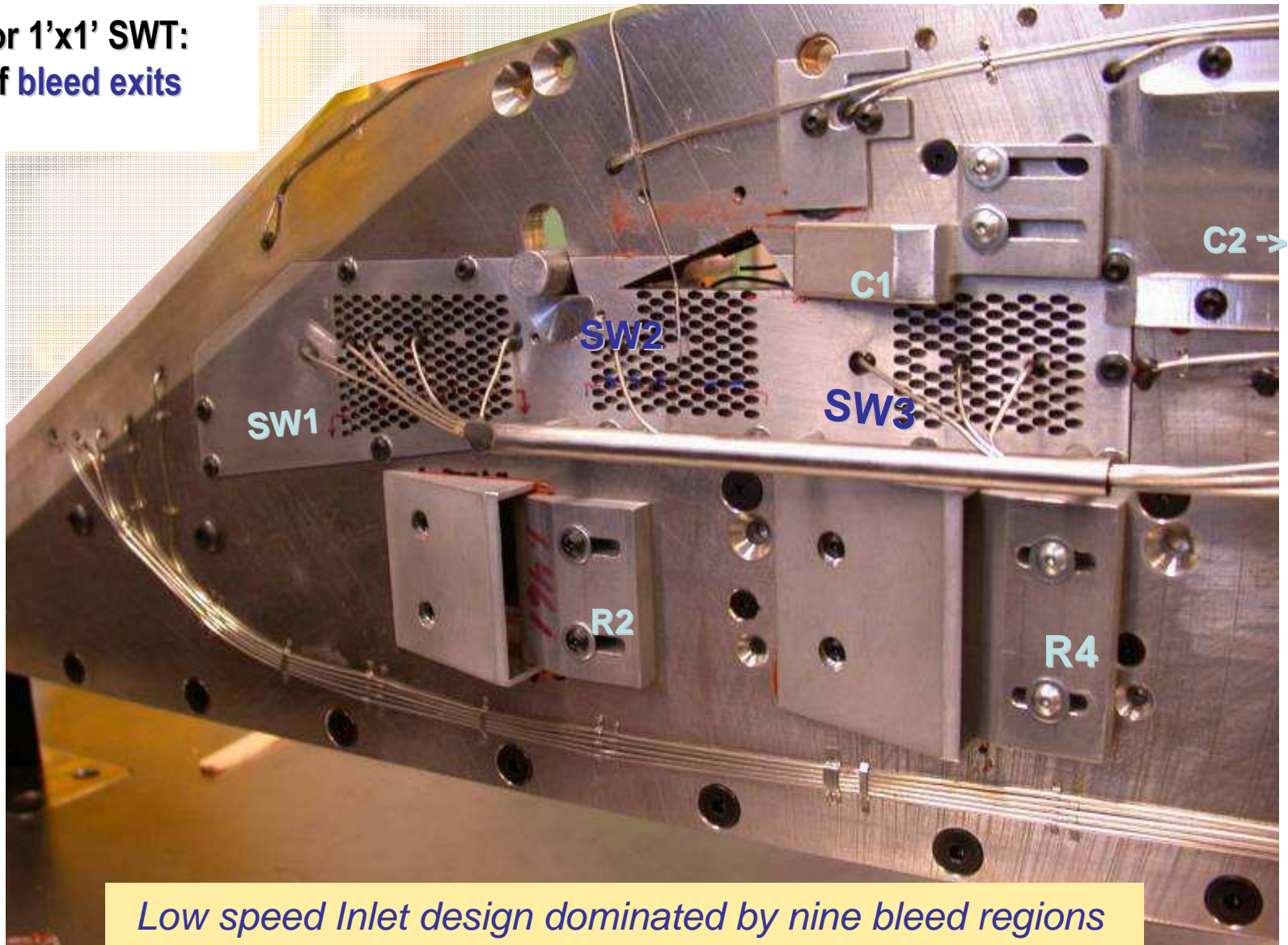**IMX model for 1'x1' SWT:**
Mechanical Design, (2/15/07)

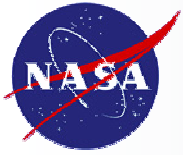**IMX Instrumentation: ~144 steady-state pressures,**
5 dynamics, 3 positions

IMX model for 1'x1' SWT:
Photo of bleed exits

*Low speed Inlet design dominated by nine bleed regions*

CFD Analyses of IMX

- Design validation: MOC/Euler/RANS
  - Shock wave structure
  - Boundary Layers
  - Throat Mach number

- Inlet performance
  - Integrated back-pressure (cane curves)

- Testing guidance:
  - Bleeds – 9 regions: extents and flow amounts,
    - CFD derived bleed
  - Throat Mach number (or contraction ratio),
    - Cowl contour
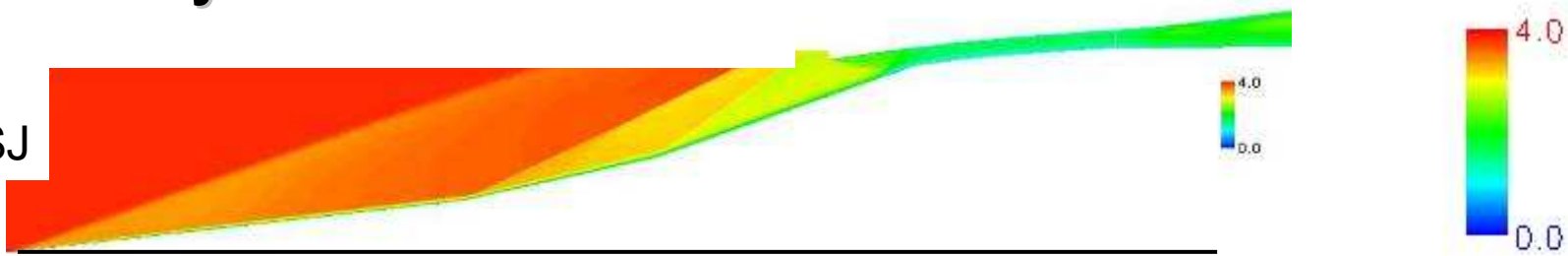 - Shoulder interaction,
    - Cutback cowl
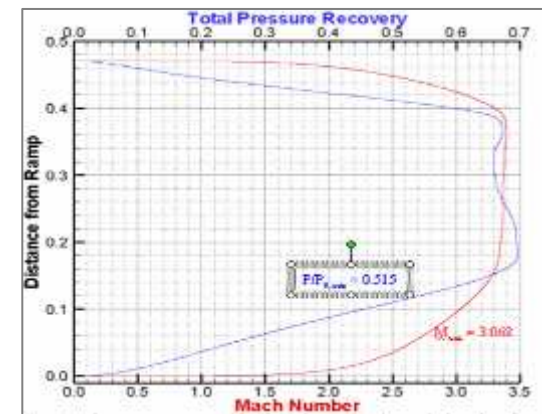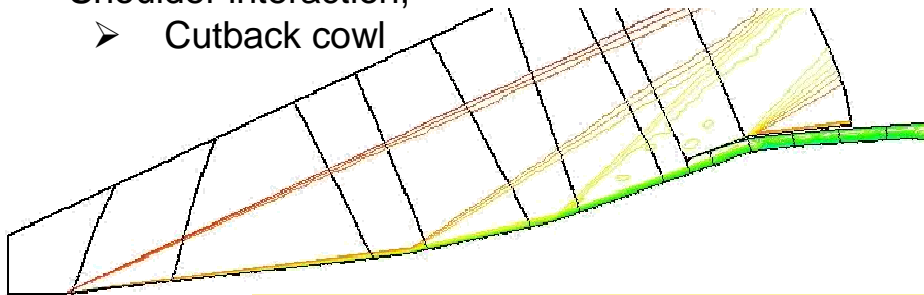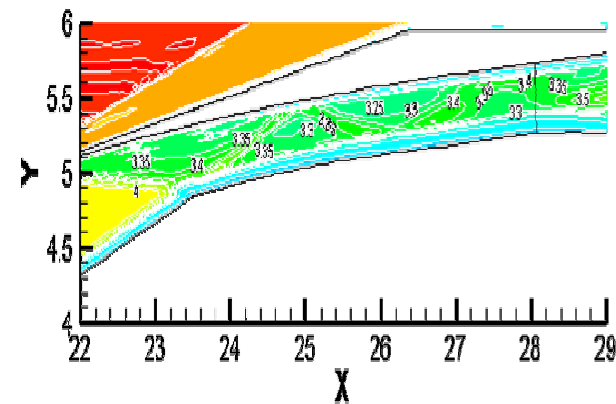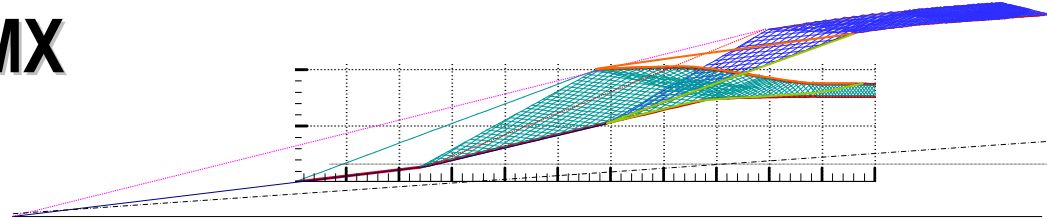
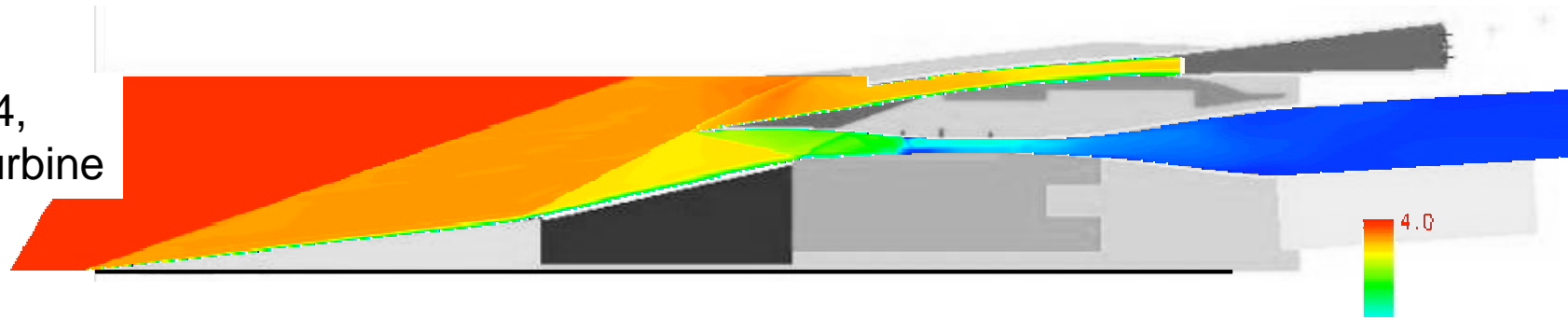*CFD has been an integral tool throughout IMX project*

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CFD Analyses of IMX
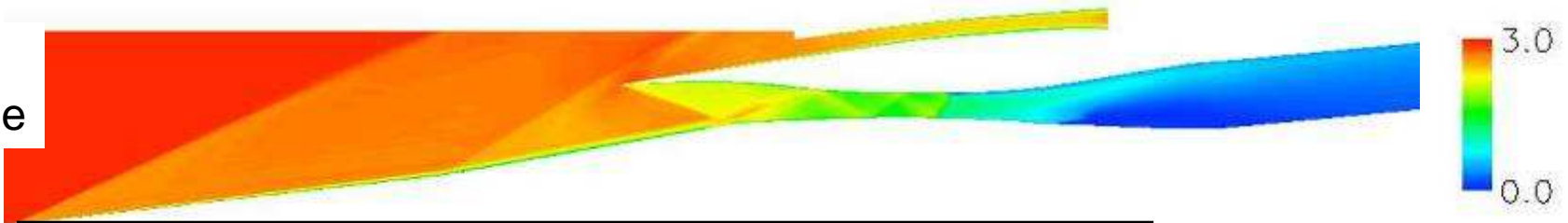

M4, DMRSJ

M4, Turbine

M3, Turbine

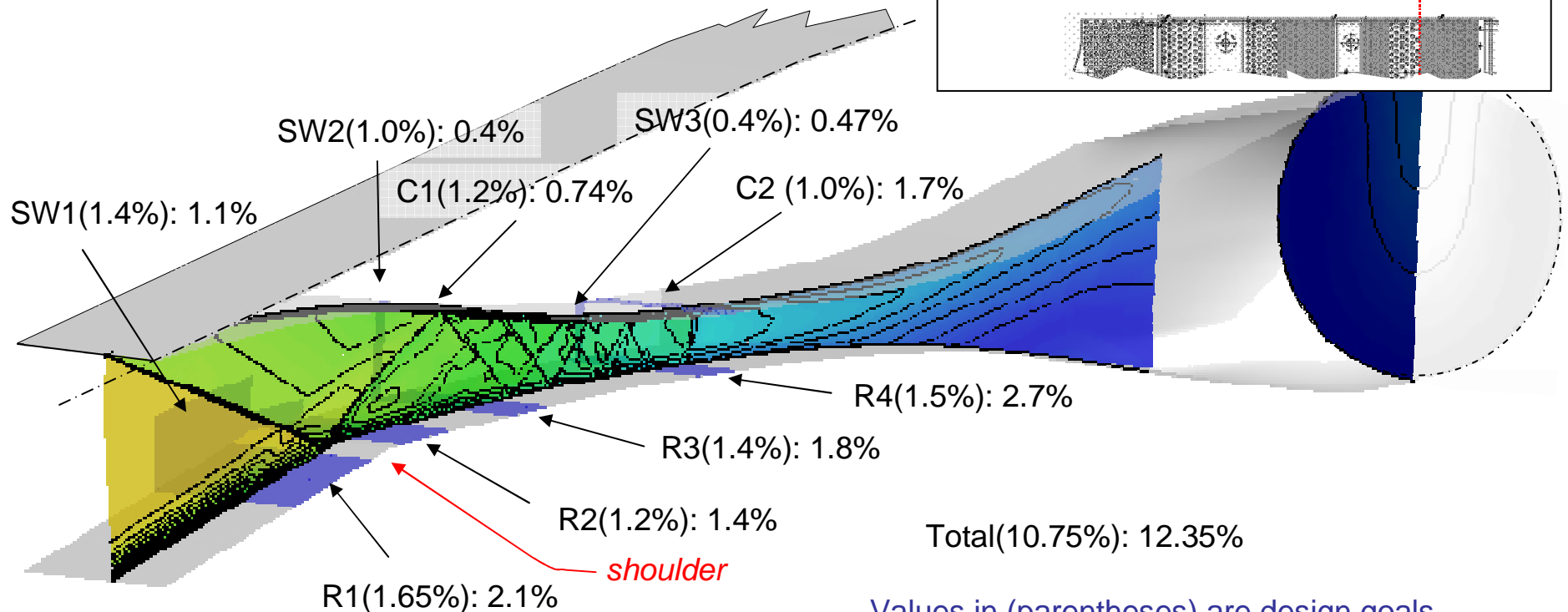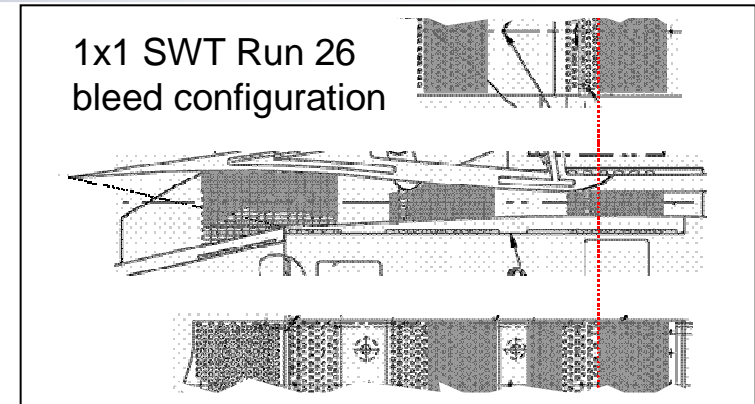*Early CFD showed expected flowfields through mode transition*

Low-Speed Inlet Bleed Study

- Bleed Model
- Adjust bleed plenum static pressures
- Match design bleed rates

1x1 SWT Run 26
bleed configuration

SW2(1.0%): 0.4%   SW3(0.4%): 0.47%

C1(1.2%): 0.74%   C2 (1.0%): 1.7%

SW1(1.4%): 1.1%

R4(1.5%): 2.7%

R3(1.4%): 1.8%

R2(1.2%): 1.4%

Total(10.75%): 12.35%

shoulder

R1(1.65%): 2.1%

Values in (parentheses) are design goals
Bleed rates are at supercritical flow
3D oblique perspective view shown (1/2 plane)
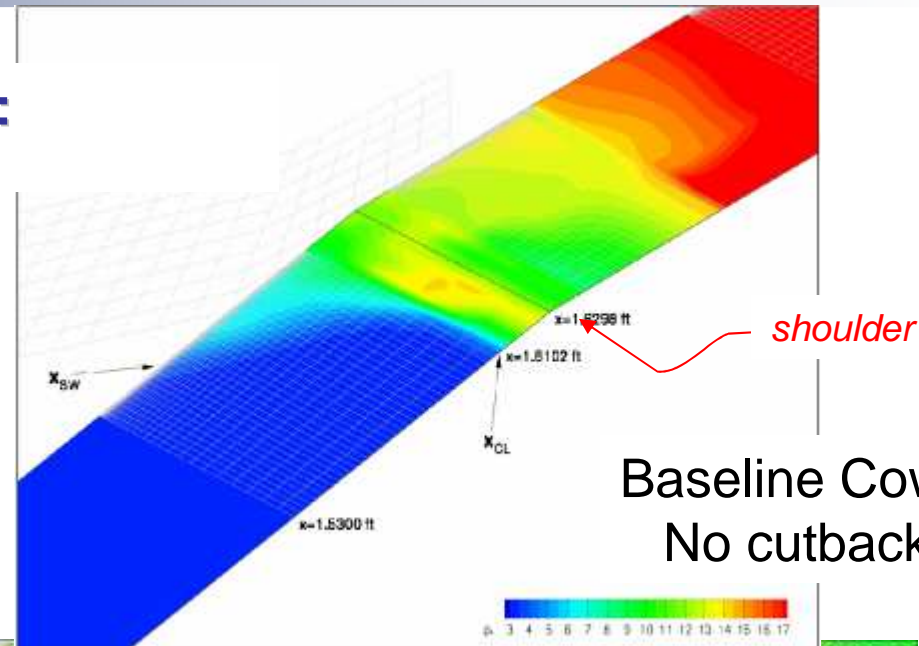
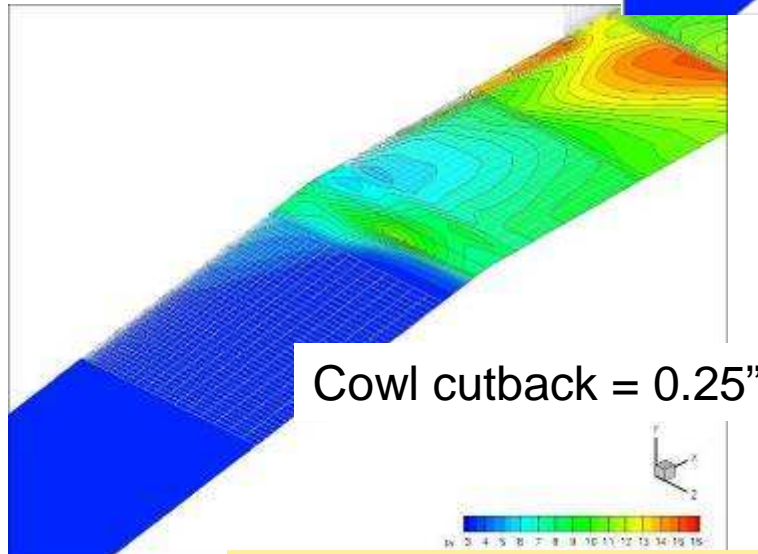*CFD able to model complexity of inlet bleed design*

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Low speed Inlet Bleed Study:

**Cowl shock cancellation /
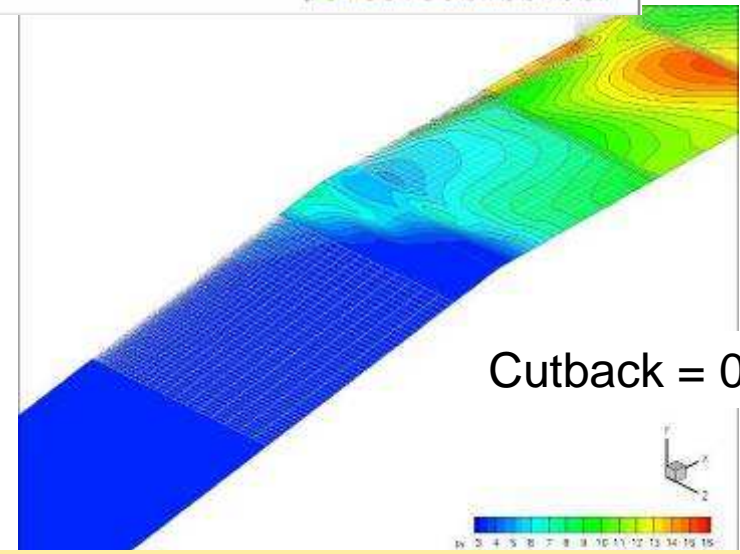Shoulder interaction**

**Effect of cutting back cowl
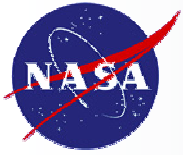leading edge on static pressures
near the ramp shoulder**

shoulder

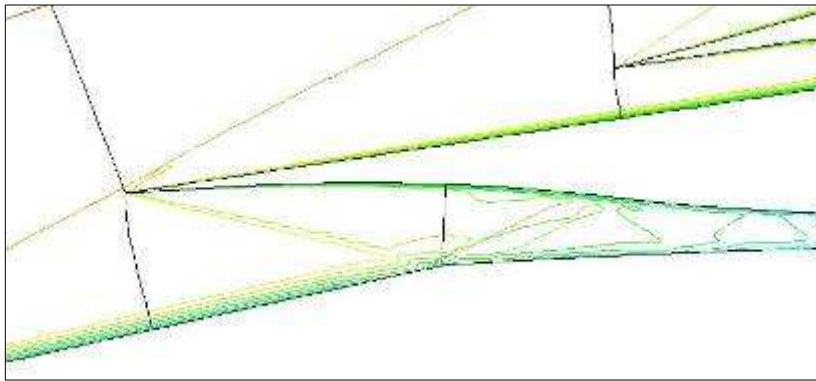Baseline Cowl,
No cutback

Cowl cutback = 0.25"

Cutback = 0.5"

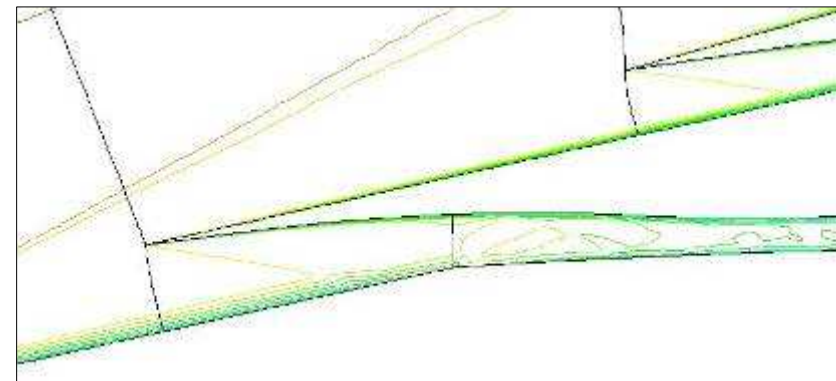*Adverse shock interaction characterized at LS inlet 'shoulder'*
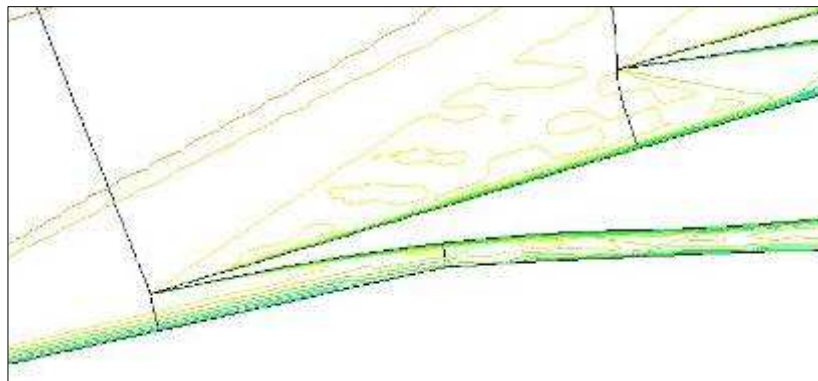
22

Mode Transition at Mach 4

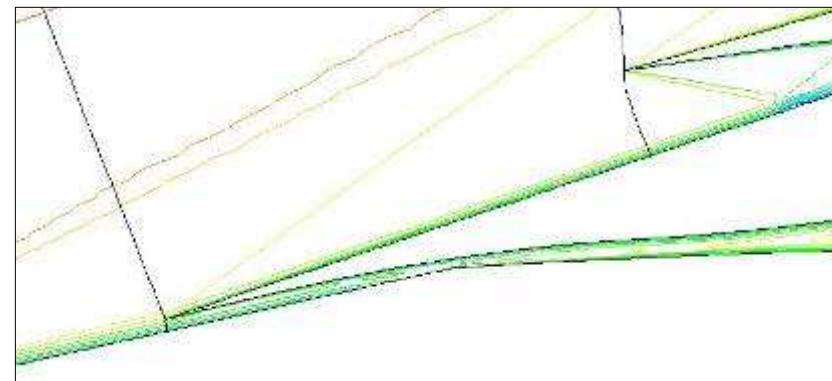Sequence of 2D steady-state solutions at 2-deg increments
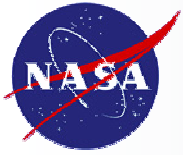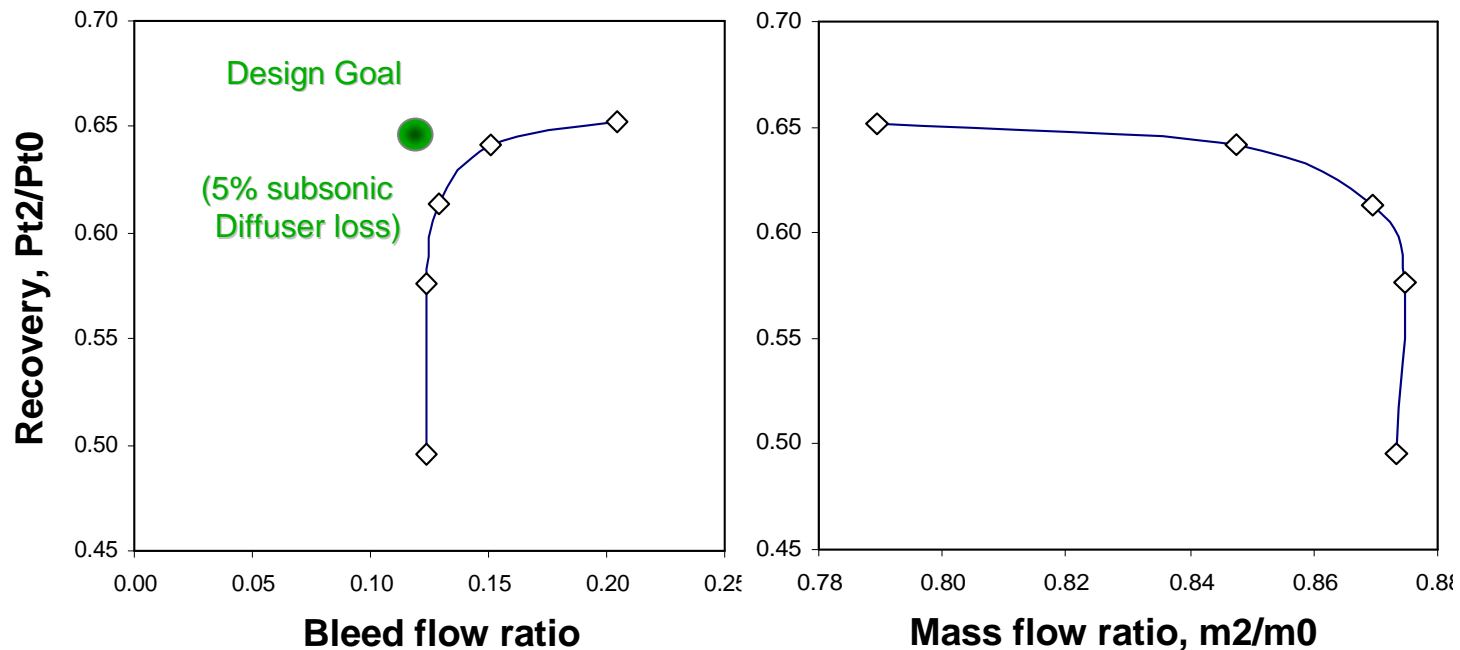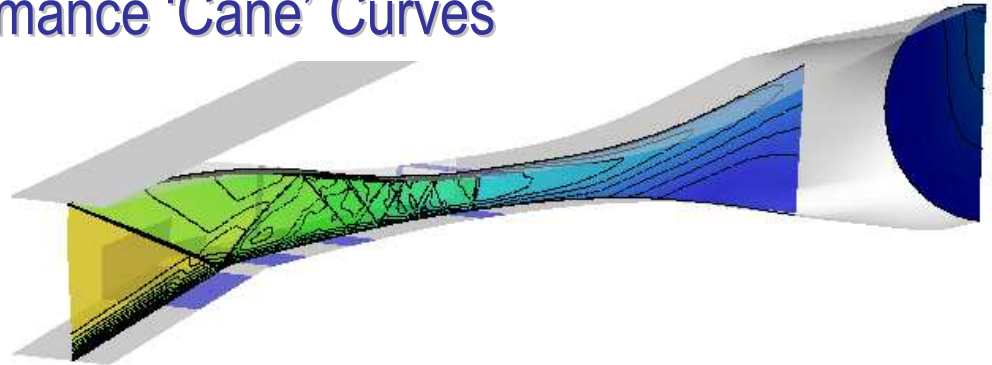

0 deg

4 deg

8 deg

10 deg

LS inlet mode transition screened by 2D CFD

TBCC Inlet Experiments and Analysis

Back-pressured CFD Study: Performance 'Cane' Curves

- Low-Speed Inlet Performance
- 1x1 SWT Run 26 bleed configuration
- Constant bleed plenum pressure b.c., (non-physical stability)

CFD suggests LS recovery performance obtainable
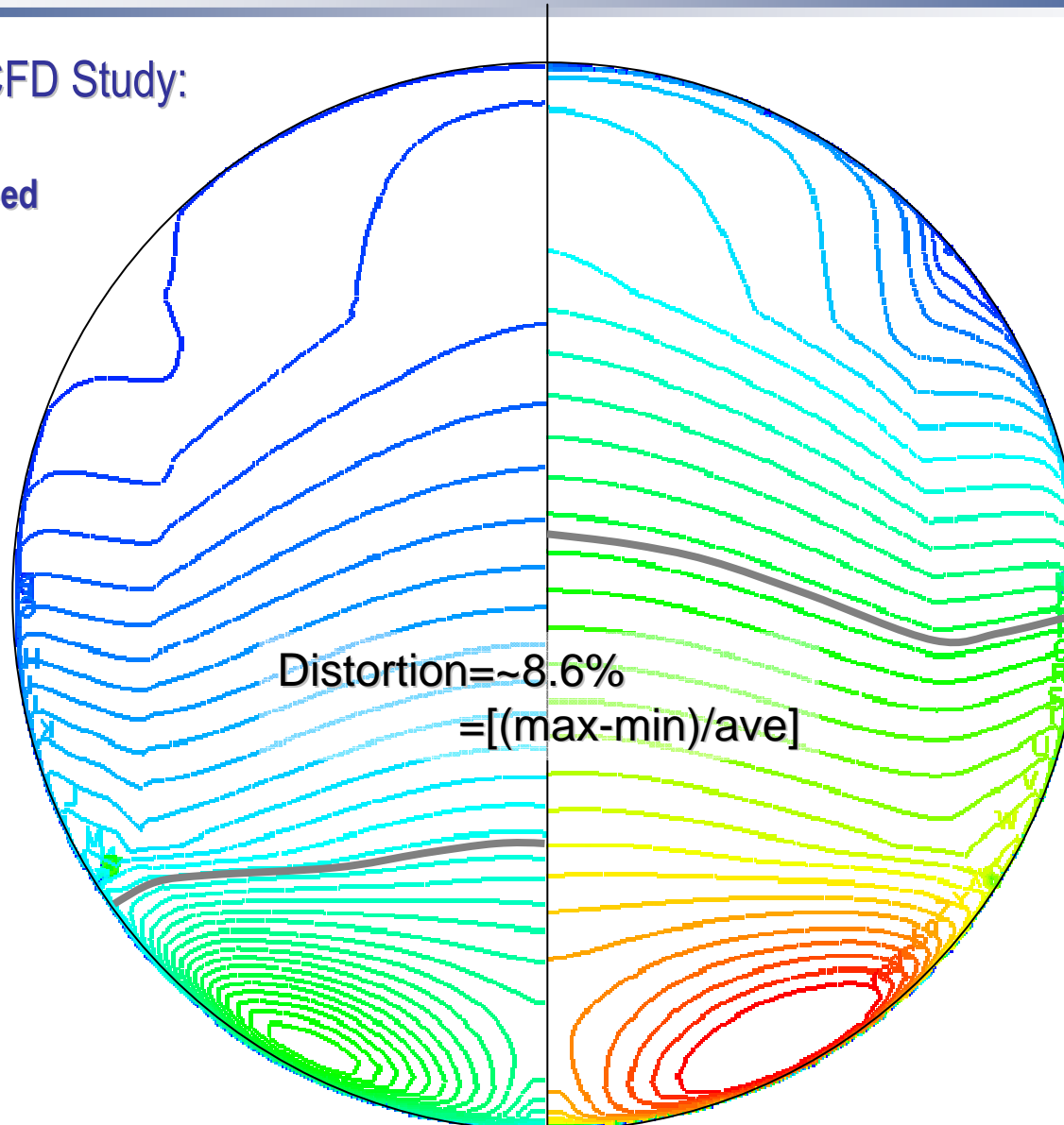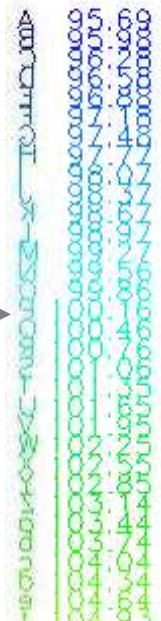
Back-pressured CFD Study:

Distortion at M4,

         - high bleed

         - no v.g.s

M4 1X1 (Back Press)

- Q = 1720 psf
- Mach 4
- Tinf = 126 R
- Pinf = 1.05 psia

Pt_{loc}/Pt_{ave}

Mach#

Distortion=~8.6%

=[(max-min)/ave]

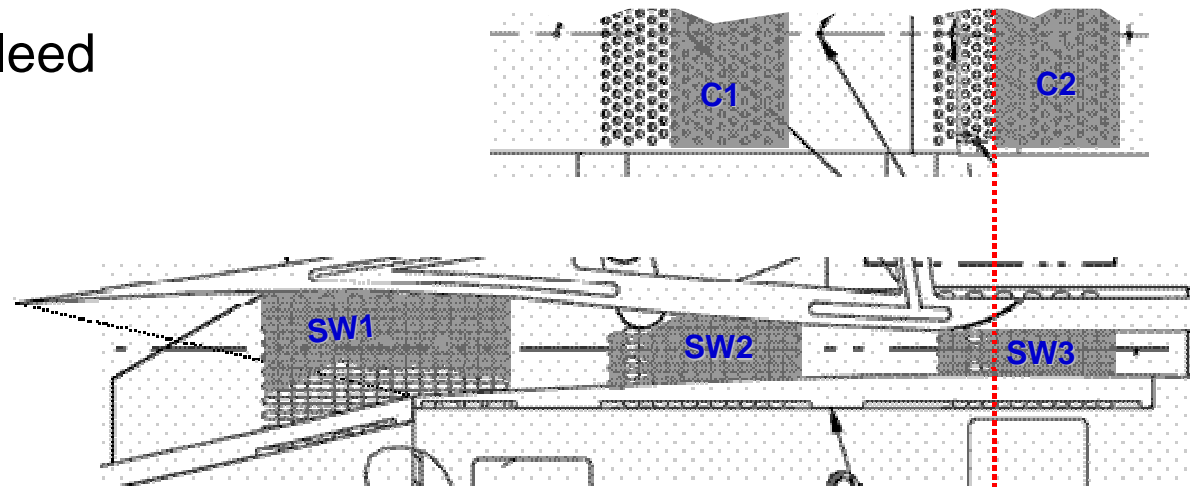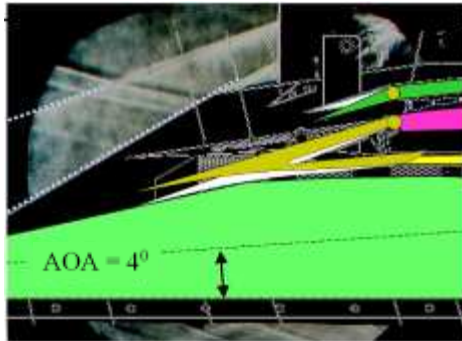*CFD indicates distortion without vortex generator may be high*

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1x1 SWT screening results, 50+runs to date

- Configurations / bleed

AOA = 4°

C1   C2

SW1   SW2   SW3

R1   R2   R3   R4

- M4 results:
  performance,
  popping behavior,
  distortion,
  Mode-x
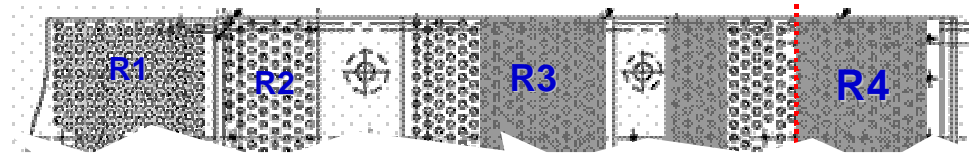
- Off-design results: recovery and distortion

1x1 experiment underway, major objectives are complete

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Mach 4 performance & Inlet Mode Transition Screening

NASA Glenn
1X1 SWT

$M_0 = 4.0$

Recovery, Pt2/Pt0

Match point

Reducing engine corrected airflow

0%

Probable best mode transition schedule

50%

Decreasing low-speed cowl angle
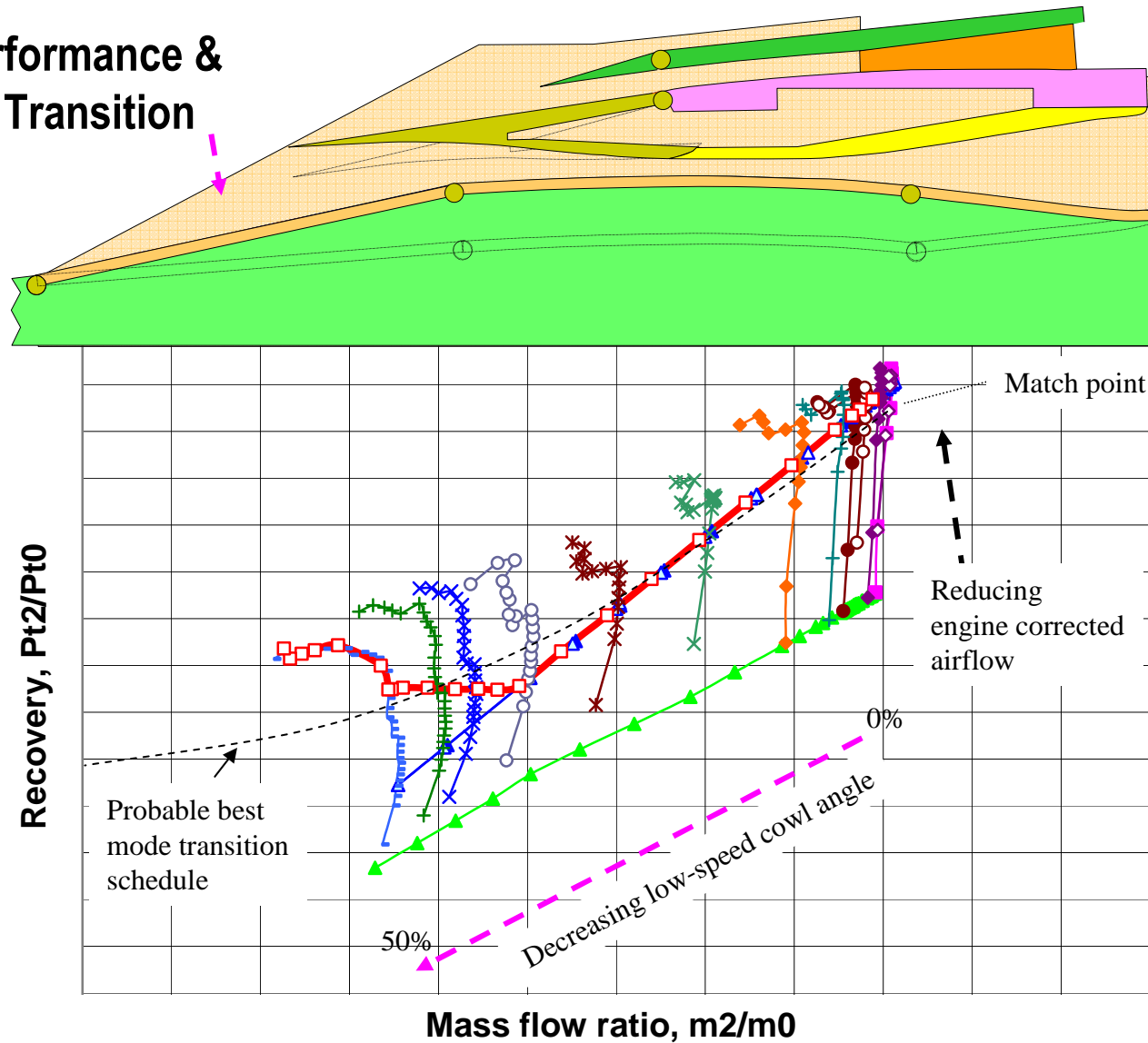
Mass flow ratio, m2/m0

Inlet performance at fixed cowl angles (engine flow variation)

Simulated mode transition (decreasing cowl angle, then combined cowl angle and reduced engine "simulated" flow)

Mach 4 performance is near design goal: mode transition smooth

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Conclusions

- TBCC Inlet design approach is valid

- CFD as a toolset is becoming helpful in inlet design
  - and continues to be part of: *Visualize, Validate, Instrument, Test plan*
  - fixed exit bleed boundary conditions needs further modeling

- Small-scale Test Results: 1x1 SWT
  - near mil-spec recovery demonstrated
  - distortion effect must be investigated further
  - cowl contour / reduced throat Mach number is desirable
  - smooth mode-x is possible

- TBCC Inlet design verified for large-scale 10x10 SWT entry
  - Mechanical design nearly complete, hardware delivery in spring '08
  - Results to date show confidence that larger-scale will perform as designed